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Factors affecting management uncertainty in U.S. fisheries and methodological solutions

Wesley S. Patrick*, Wendy Morrison, Mark Nelson, Rosa L. González Marrero

NOAA-Fisheries, Office of Sustainable Fisheries, 1315 East-West Highway, Silver Spring, MD 20910, USA

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ABSTRACT

The management of marine fisheries is often based on a system of target and limit reference points, and contains significant amounts of scientific and management uncertainty that need to be interpreted and reconciled by managers. While scientific uncertainty has been thoroughly studied, described, and techniques have been developed to address this type of uncertainty; studies of management uncertainty are lacking and of the few studies available most are theoretical in nature. We evaluated 17 U.S. fisheries to describe how management uncertainty varies among management regimes and identify some potential factors that drive these variances. Our analysis found that a manager's ability to keep a fishery at or under the targeted catch level can vary substantially among fisheries, depending on the sector of the fishery, the management regime being used, the frequency at which landings are reported, and the magnitude of inter-annual target variability. Within our study, reporting frequency and the type of management regime being used seemed to describe the majority of the variance we observed among fisheries.

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1. Introduction

Managing living marine resources presents a daunting challenge, because managers must try to quantify the biomass of a resource that is difficult to census and then regulate fishing effort so as to optimize catch while not overexploiting the resource. To deal with uncertainty, managers of living marine resources often use *adaptive management* and *precautionary principles* for setting harvest levels (FAO (Food and Agriculture Organization), June 1995; Parma et al., 1998; Hilborn et al., 2001; Allan and Curtis, 2005).

Adaptive management, or more specifically *passive* adaptive management, is an approach to managing natural resources that encourages learning from the outcomes of implemented policies and strategies (Allan and Curtis, 2005; Walters, 2007). However, this approach can reflect socio-economic and political biases, which could lead to inadequate regulations for sustaining the resource (Allan and Curtis, 2005; Walters, 2007; Rosenberg et al., 2006). Adaptive management is therefore usually paired with the precautionary principle, which holds that, where the likely impact of resource use is uncertain, priority should be given to maintaining the productive capacity of the resource (FAO (Food and Agriculture Organization), June 1995).

In the United States and in other areas around the world, precautionary fishery management is often based on a system of *target* and *limit* reference points (Caddy and Mahon, 1995; Ryans, 2007; Shertzer et al., 2010). These reference points are typically defined in terms of exploitation rates, levels of catch in weight, or numbers of fish. The limit reference point is usually a level of harvest that produces the maximum sustainable yield of a fish stock, while the target reference point is a level of harvest that is set below the limit and is based on the ecological, social, and economic objectives of the fishery. Lowering the target below the limit reference point can provide a risk buffer against frequent overexploitation and potential depletion of the stock's biomass overtime (Shertzer et al., 2010).

Although the system of setting target and limit reference points may seem straight forward at first, both reference points contain significant amounts of uncertainty for scientists and managers to reconcile. Limit reference points are usually set by fishery scientists, who determine the maximum sustainable yield of a stock based on stock population dynamics data that have statistical and structural (e.g., stock-recruitment relationships, catchability, etc.) uncertainty; often referred to as scientific uncertainty. Conversely, target reference points have historically been set by fishery managers, who consider the scientific uncertainty in the estimate of the limit,

* Corresponding author. Tel.: +301 427 8566; fax: +301 713 2114.
E-mail address: Wesley.Patrick@noaa.gov (W.S. Patrick).

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the perceived needs of their stakeholders, and effectiveness of their management regime to achieve a level of targeted catch without exceeding the limit. The uncertainty of the management regime—including regulations, catch monitoring, and other management controls—in achieving the target level of catch is often called management uncertainty. Although scientific uncertainty and management uncertainty are broadly recognized as issues facing fisheries management, to date most of the attention has focused on scientific uncertainty (Holt and Peterman, 2006; Fulton et al., 2011).

Management uncertainty takes various names in the scientific literature, among them: implementation error (Rosenberg et al., 1993; Dichmont et al., 2006; Essington, 2010); implementation uncertainty (Shertzer et al., 2010; Fulton et al., 2011; Francis and Shotton, 1997; Prager et al., 2003); partial controllability (Williams, 1997); structural uncertainty (Charles, 1998); outcome uncertainty (Holt and Peterman, 2006); and catch control (Melnychuk et al., 2012). Despite the long list of synonyms for this type of uncertainty, the literature mostly describes only the theoretical concept of management uncertainty, without investigating its realized impact on maintaining fish stocks at sustainable levels. A literature review discovered only five articles that estimated the impacts of management uncertainty on fishery management performance.

Of these five articles, Shertzer et al. (2010), Dichmont et al. (2006), and Prager et al. (2003), provide theoretical examples on how management uncertainty could be taken into account when setting target levels of catch, and Essington (2010) and Melnychuk et al. (2012) provide a thorough analysis of how management uncertainty differs among fishery management regimes. Both Essington (2010) and Melnychuck et al. (2012) focus on the effectiveness of catch share programs for maintaining catch at targeted levels and exploitation rates, compared to quota-based and effort-based fisheries. However, none of these articles evaluates the underlying reasons different management regimes outperformed others, nor did they consider how variability in fisheries changes through time due to adaptive management.

The purpose of this article is to more fully describe the impacts of management uncertainty on fishery performance and why some management regimes may exhibit lower levels of management uncertainty than others. In Section 2, we evaluate 17 U.S. fisheries, in an effort to show how management uncertainty can affect the ability of fishery managers to achieve management goals such as optimum yield. Following this summary of impacts on fishery performance, in Section 3 we provide some simple methods of quantifying and accounting for management uncertainty in a fishery based on the factors we evaluated. These methods should help fishery managers estimate management uncertainty, and account for this uncertainty when developing management measures.

2. Evaluating management uncertainty variability among fisheries

For the purposes of this article, we measure management uncertainty on an annual basis as the ratio of actual harvest to the targeted harvest level (ATR):

$$ATR = \text{Actual harvest}/\text{Targeted harvest} \tag{1}$$

We chose this measure because it shows both negative and positive effects, both harvest levels are reported annually by fishery managers, and it represents the end point in management uncertainty—i.e., did managers meet their target? Based on the findings of Essington (2010) and Melnychuk et al. (2012), we know that the variability of management uncertainty will depend on the management regime of the fishery. We evaluated 17 U.S. fisheries targeting 12 different species, covering a variety of management characteristics including various sectors (i.e., commercial versus recreational), management styles, and reporting frequencies (Table 1). These fisheries were also chosen because they have a relatively long time series of targeted and actual landings data (i.e., 5–20 years). Throughout this article we use the terms landings

Table 1
Fisheries examined indicating their management system, reporting frequency, average ex-vessel value (in 2010 USD), and years of analyzed data.

Region	Council	Fishery	Sector	Management type	Reporting frequency	Years analyzed
Alaska	North Pacific	IFQ Halibut	Commercial	Catch share	Daily	1995–2009
		CDQ Halibut	Commercial	Catch share	Daily	1995–2009
		IFQ Sablefish	Commercial	Catch share	Daily	1995–2009
		BS AFA Pollock Inshore	Commercial	Catch share	Weekly	1999–2009
		BS AFA Pollock Mothership	Commercial	Catch share	Daily	1999–2009
		BS C/P Pollock	Commercial	Catch share	Daily	1999–2009
Northeast	Mid-Atlantic	Black sea bass	Commercial	In-season	Weekly	1998–2008
			Recreational	In-season	2 Months	1998–2008
		Ocean quahog	Commercial	Catch share	Daily	1996–2005
		Surf clam	Commercial	Catch share	Daily	1996–2005
		Summer flounder	Commercial	In-season	Weekly	1993–2007
			Recreational	In-season	2 Months	1998–2007
		Monkfish	Commercial	Post-season	Yearly	2000–2009
Northeast	New England	Monkfish	Commercial	Post-season	Yearly	2000–2009
		Red crab	Commercial	Post-season	Yearly	2002–2009
Southeast	Gulf of Mexico	King mackerel	Commercial	In-season	2 Weeks	1986–2005
			Recreational	In-season	2 Months	1986–2005
			Commercial	In-season	2 Weeks	1990–2005
			Commercial	Catch share[a]	Daily	2007–2008
			Recreational	In-season	2 Months	1991–2005
Southeast	South Atlantic	King mackerel	Commercial	In-season	Monthly	1986–2005
			Recreational	In-season	2 Months	1987–2005
		Golden tilefish	Commercial	In-season	2 Weeks	1995–2010

[a] The 2006 data for commercial red snapper fishery was not analyzed because this fishery transitioned from an in-season to a LAPP management system in 2006.

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and catch interchangeably because some fisheries manage their harvest quotas according to landings and others according to catch (fish landed + bycatch mortality). This difference is not expected to bias our results, because when bycatch is not monitored as part of the targeted harvest quota it is accounted for in other ways – incorporated into the stock assessments and the setting of overfishing limits, or through separate accountability measures specific to bycatch not evaluated here. Additionally, in most cases these fisheries are comprised of only a few stocks, which reduced the complexity of our analysis because some stocks in multispecies fisheries are never fully utilized due to catch limits of other stocks in the fishery being reached first; thus, closing the fishery.

In order to determine when the catch was under or over the target, we first calculated the ATR for each year of each fishery (Fig. 1). To compare the differences in management uncertainty among management regimes, we compared ATRs across the regimes using the non-parametric Kruskall-Wallis rank test, since the data were not normally distributed and Levene's test in most instances found the data to have unequal variances. We also completed a Chi-square (χ^2) contingency table test to determine whether the proportion of times catch exceeded the target was similar across regimes. The following sections provide an overview of how the management regimes differed in terms of ATRs, and continues with similar analysis of how different factors related to a fishery or management regime could possibly affect management uncertainty related to reporting frequency, inter-annual variability, and fluctuations in biomass.

2.1. Management regimes

Three types of management regimes were evaluated among the 17 fisheries: catch share programs, in-season management, and post-season management. In catch share fisheries, specific amount of landings are allocated to individuals or groups of individuals in the fishery, see (Essington, 2010). Therefore, each individual or group is responsible for tracking their actual landings so as not to exceed their individual quota and are penalized for any overages they may incur. When managers use in-season management, they monitor landings during the fishing season and, when landings are near the targeted level, they take actions to reduce catch (e.g., reduce bag limits, close areas to fishing, or close the fishing season entirely) in an attempt to avoid exceeding the target. Post-season management is a method of accounting for landings relative to the target after the fishing season has ended.

Like Essington (2010), we found a significant difference ($P < 0.001$) in the ATR variance among the management regimes when commercial and recreational sectors were grouped together (Fig. 2), but no significant difference among the median ATRs ($P = 0.547$) (Table 2). Among the three management regimes, catch share fisheries exhibited the lowest variance, followed by in-season fisheries, and post-season fisheries (Table 2). We also found a significant difference in the proportion of times the catch exceeded the target (i.e., ATR > 1) (df = 2, $\chi^2 = 43.2$, $P < 0.0001$). Similar to the variances we observed, catch share fisheries exceeded the target only 2% of time ($n = 96$), while in-season (38%; $n = 172$) and post-season fisheries (36%; $n = 28$) exceeded the target more often.

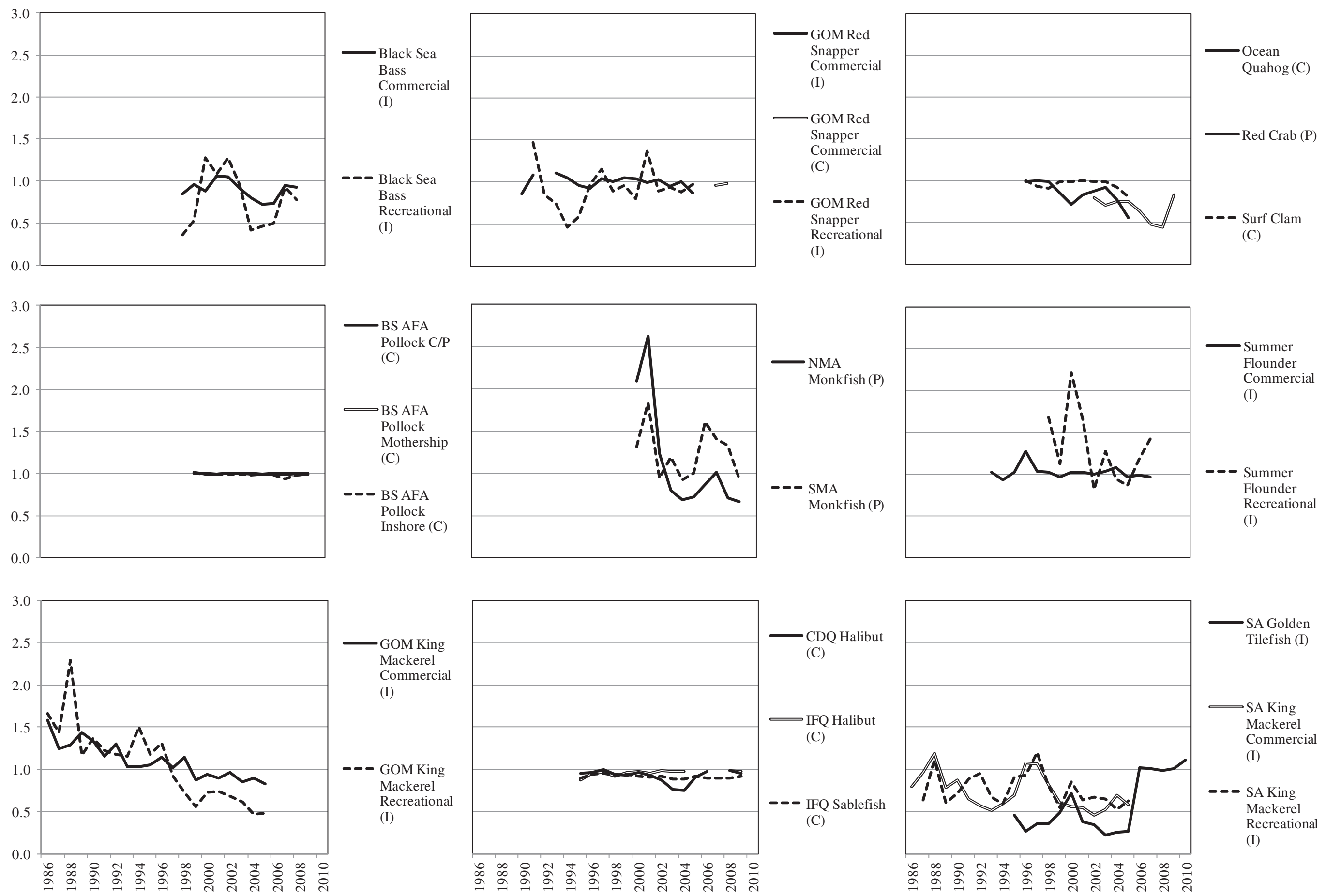

Fig. 1. Actual landings: target catch ratios (ATRs) for the 22 commercial and recreational fisheries examined; I = in-season, P = post season, and C = catch share management.

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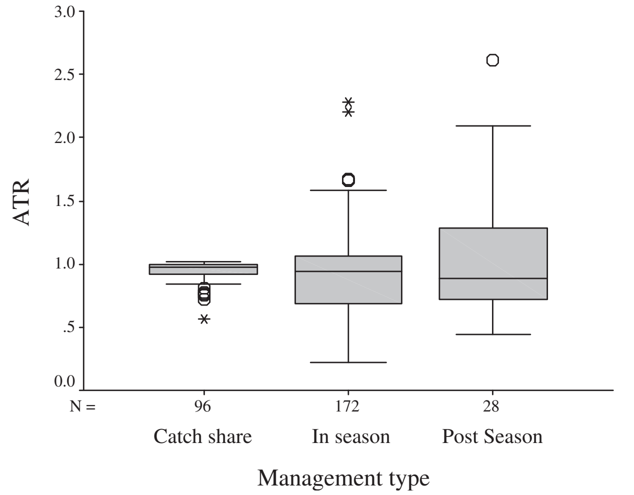

Fig. 2. Box plot of management types and observed ATRs. Points with an open circle indicate outliers that 1.5 times greater than 25th or 75th percentile, and asterisks indicate extreme outliers that are 3.0 times greater.

2.2. Commercial and recreational sectors

We also limited the tests from above to commercial sector data to determine whether inclusion of recreational data (all associated with in-season management) confounded the differences we detected between the commercial management regimes (Table 2). The results did not change; there was still a significant difference in variability ($P < 0.001$), no significant differences between median ATRs ($P = 0.912$), and a significant difference in the proportion of times the catch exceeded the target ($df = 2$, $\chi^2 = 43.8$, $P < 0.0001$).

We did, however, find a significant difference ($P < 0.001$) in a general comparison between commercial and recreational fisheries variances. For our analysis, recreational fisheries included both private recreational fishermen and for-hire charter fishermen. We did not find any significant differences ($P = 0.323$) between the median ATRs (Table 2; Fig. 3), nor was there a significant difference in the proportion of times the fisheries exceeded their target ($df = 1$, $\chi^2 = 3.03$, $P = 0.08$). These results did not change when we repeated our comparisons of commercial versus recreational data, but limited the commercial fisheries to those that used in-season management (because all of the recreational fisheries examined were classified as in-season management fisheries) (Table 2).

Table 2
Comparison and descriptive statistics of fisheries ATRs based on sector, management type, and reporting frequencies (n = number of ATRs). P-values are also provided based on differences in ATR variance using Levene's tests, ATR medians using Kruskal–Wallis tests, and the proportion of times the catch target was exceeded using Chi-square tests.

Category	n	Mean	Median	Variance	*P value* Variance	Median	Target exceeded
Sector							
Commercial	221	0.933	0.963	0.067	<0.001	0.323	0.080
Recreational	75	0.953	0.890	0.150			
Sector (In-season management type)							
Commercial	97	0.885	0.959	0.073	0.006	0.877	0.470
Recreational	75	0.953	0.890	0.150			
Management type (all sectors combined)							
Catch share	96	0.947	0.975	0.005	<0.001	0.547	<0.0001
In-season	172	0.915	0.937	0.107			
Post-season	28	1.047	0.891	0.249			
Management type (commercial sector)							
Catch share	96	0.947	0.975	0.005	<0.001	0.912	<0.0001
In-season	97	0.885	0.959	0.073			
Post-season	28	1.047	0.891	0.249			
Reporting frequency							
Daily	85	0.942	0.967	0.006	<0.001	0.002[a]	<0.001
Weekly	37	0.972	0.988	0.009			
2 Weeks	51	0.906	1.004	0.103			
Monthly	20	0.727	0.667	0.044			
2 Months	75	0.953	0.890	0.150			
Yearly	28	1.047	0.981	0.249			

[a] Dunnett T3 post hoc t-test identified monthly reporting was responsible for the finding of significant difference, and this category of reporting is represented by one underutilized fishery.

2.3. Reporting frequency

Some of the variability observed between management regimes and sectors of those fisheries may be explained by differences in reporting frequency, because the reaction time of managers or individuals (in the case of catch shares) to respond to or predict overages of a target is dependent on reporting frequency. For example, recreational fishery landings are reported in 2-month intervals; whereas, commercial in-season and catch share fisheries generally report their landings more frequently. Lastly, while post-season fisheries may be monitored throughout the year, no management actions are taken until the end of the fishing year, so they are noted here as reporting annually.

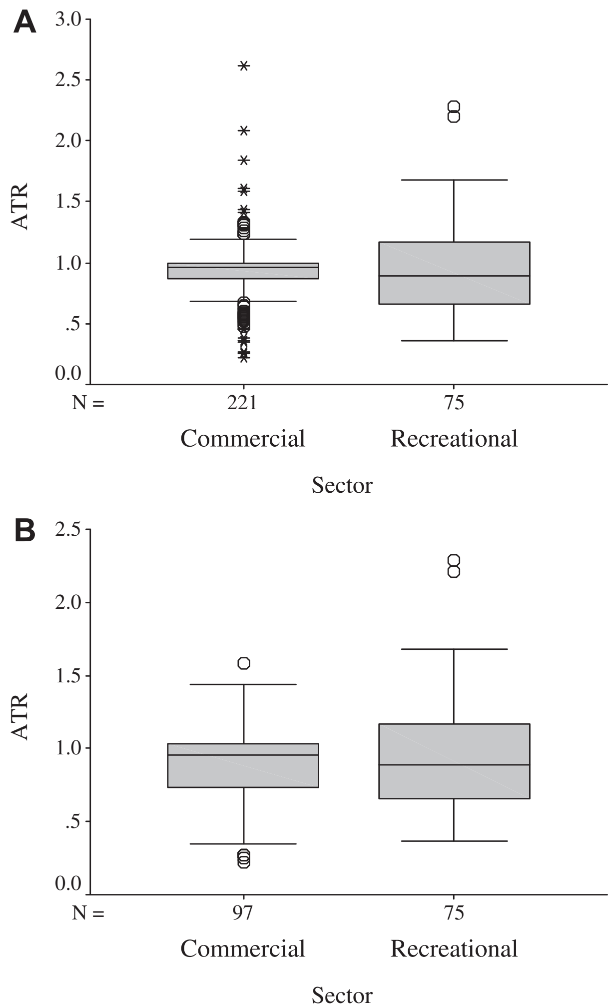

Fig. 3. Box plot of recreational and commercial fisheries observed ATRs. Plot A includes all commercial management types and plot B restricts comparison to only in-season management because both sectors are managed in-season.

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Results from a contingency table analysis revealed there was a significant difference in the proportion of times the fisheries exceeded their target between the different reporting frequencies (df = 4; $\chi^2 = 43.5$, $P < 0.001$). We also found significant differences ($P < 0.001$) in the variances among the various reporting frequencies examined. Daily reporting frequency had the lowest frequency of exceeding the target (2%, $n = 85$) and variance ($\sigma^2 = 0.006$), followed by weekly, monthly, bi-weekly, bi-monthly, and annually (see Table 2 and Fig. 4).

Median ATRs were also significantly different ($P = 0.002$). To determine which reporting frequency category was significantly different, we used a Dunnett T3 post hoc *t*-test which is a parametric test used when data sets have unequal variances and sample sizes. The post hoc *t*-test showed that only the monthly reporting category was significantly different from other reporting categories (*P* ranged from 0.001 to 0.112). However, it is important to note that all of the monthly reporting data come from the South Atlantic king mackerel fishery that has historically kept its actual catch relatively low compared to the target (median ATR = 0.667), while other reporting frequencies had median ATRs ranging from 0.890 to 1.004 (Table 2, Fig. 4). Thus, we believe this finding of significance for monthly reporting frequency is a due to the limited and biased data.

2.4. Inter-annual target variability

We evaluated whether management uncertainty changes relative to the degree to which targets for the fishery changes from year to year, based on the assumption that trying to hit a moving target may be more difficult than hitting a target that remains the same from year to year. We arbitrarily categorized the variability of targets using thresholds of 5% and 20% change, resulting in five categories: 1) <−20% decreasing target; 2) −20% to −5% decreasing target; 3) −5% to 5% no change in target; 4) 5% to 20% increasing target; and 5) >20% increasing target. Using the Chi-square test, when all management types were grouped together, we found a significant difference among the five categories in the proportion of times the target was exceeded (df = 4, $\chi^2 = 13.14$, $P = 0.010$). We observed that the target was exceeded 40% and 39% of the time when targets were decreased more than 20% or increased more than 20%, respectively. For changes of lower magnitude (<+/−20%) the target was exceeded no more than 25% of the time (Fig. 5).

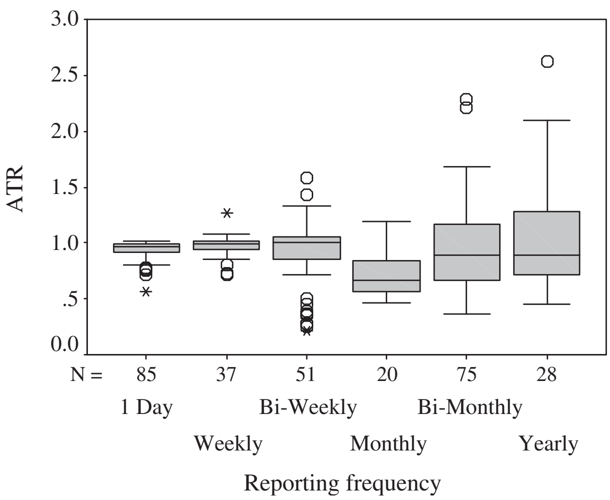

Fig. 4. (A) Box plot of reporting frequency and observed ATRs, noting that less frequent reporting of catch or landings results in higher degrees of variability and management control.

2.5. Biomass variability

We also considered the finding of Essington (2010), who found no significant differences in the variance or mean biomass of stocks when they were managed under catch shares versus other management controls. We evaluated this hypothesis by looking at the five catch share and five non-catch share stocks from this study that had spawning stock biomass data for at least 10 years (Table 3). To compare variability between catch share and non-catch share stocks, biomass estimates were first standardized by dividing annual biomass by the mean biomass for each stock. This removed differences due to overall stock size and reporting units. After standardizing, the mean biomass of each stock through time became 1.0, but the variance between stocks was now comparable. We found that the variances between catch share (variance = 0.0144) and non-catch share (variance = 0.5929) stock biomasses were significantly different ($P = 0.03$).

This finding is expected given that consistent management of catch levels should lead to consistent biomass levels, if scientific uncertainty is not an issue, meaning stock recruitment relationships are well known and can be projected with high degrees of scientific certainty. This idea that biomass should be maintained at a relatively constant level is also one of the primary objectives in U.S. fisheries – to maintain biomass at levels that support maximum sustainable yields. Assumptions of low scientific uncertainty are likely true for the catch share stocks we evaluated, but non-catch share stocks we evaluated likely have higher levels of scientific uncertainty because less is known about their recruitment relationships and stock assessments are only updated every 3–5 years. Thus, the finding that biomass variability is less for catch share-stocks may be an artifact of the limited data we analyzed and should only be viewed as an observation that differs from Essington (2010).

3. Accounting for management uncertainty

In the previous section we described the variability in ATRs observed among such factors as sectors, management regime, reporting frequency, etc. However, such analyses do not describe how such information can be used by managers and scientist to account for management uncertainty as they develop fishery regulations or other planning actions. This section provides some potential methods of accounting for management uncertainty and setting limit and target levels of catch.

3.1. Learning curve

Only a few authors have demonstrated how management uncertainty could be accounted for in setting limit and target levels of catch; Dichmont et al. (2006) calculated the variance of management uncertainty, whereas Shertzer et al. (2010) and Prager et al. (2003) created a probability distribution function (PDF) based on the coefficient of variation of management uncertainty observed overtime. These approaches are appropriate if the ATR variance is constant through time, but in theory the variance in management uncertainty should decline through time if managers are using a passive adaptive management approach. Consequently, fisheries should display some form of learning curve through time where ATR variance is declining and the median ATR becomes closer and closer to 1.0. Where learning curves are observed and management uncertainty is being estimated based on past performance of hitting catch targets, it may be prudent to use a weighted average of variance so that the most recent years are weighted more heavily than in past years when performance was less accurate.

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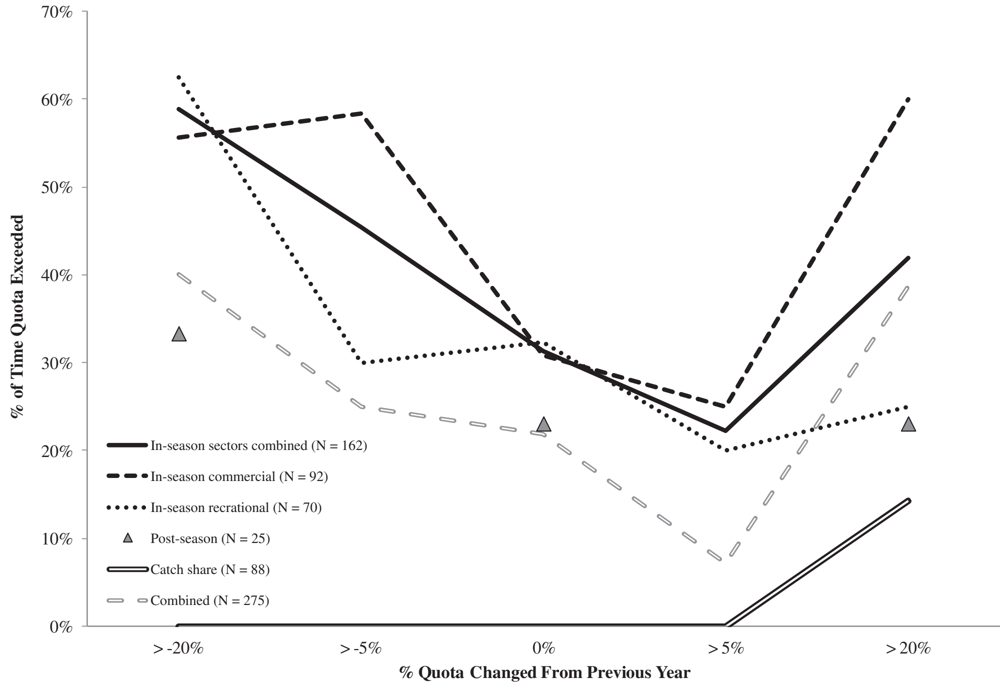

Fig. 5. The percentage of times the target was exceeded given the percent change in the target from the previous year. Post-season fisheries did not have target changes in the −20% to −5% or the 5%–20% ranges; therefore there is no line connecting the data points.

However, Charles (1998) noted that uncertainty in predicting how much can be sustainably taken from the marine environment cannot be precisely predicted. Thus, the idea that a learning curve is always smooth and deterministic may not hold up in every case, and may only ever occur when scientific uncertainty is adequately accounted for in the management process. Determining whether a learning curve is present can be performed by plotting the ATRs and evaluating whether the ATRs have systematically converged to or near 1.0 through time (Fig. 1).

In this analysis, only two of the 17 fisheries seemed to exhibited signs of a learning curve: northern management area monkfish fishery, and the Gulf of Mexico king mackerel fisheries (Fig. 1). Where variances in the ATR are random or do not show a clear trend, it may be appropriate to calculate just the average variance or produce a PDF as others have done. Where trends are observed, but do not appear to be constant or following a learning curve, managers should determine how to weight each ATR data point through time.

A review of the fishery's management history may be an important first step to help explain why a fishery's ATR has changed through time. For example, the Gulf of Mexico King Mackerel Fishery (Fig. 1) shows a general decline of ATR over the period 1985 to 2005. The point at which the ATR falls below 1.0 occurs in 1999, which corresponds to implementation of Amendment 8 of the Coastal Pelagics Fishery Management Plan that manages king mackerel in the Gulf of Mexico. Amendment 8 prohibited certain gear types historically used in the fishery, allowed managers to set vessel trip limits, closed seasons, and most importantly, clarified that the Regional Administrator of NOAA Fisheries could close the fishery when targets were reached. Since the implementation of Amendment 8, the ATR has remained relatively constant, so if the managers wanted to account for management uncertainty based on prior performance they could either weight the years 1999–2005 the heaviest or they could simply only use the ATR data points after 1999 to estimate the variance or produce a PDF, because only these points represent the current management regime for the fishery.

Table 3
The list of catch share and non-catch share fisheries used to examine the variance in spawning stock biomass.

Fishery	Management regime	Spawning stock biomass	
		N	Variance
IFQ Pacific halibut	Catch share	11	0.037
IFQ sablefish	Catch share	15	0.003
AFA Pollock	Catch share	11	0.028
Ocean quahog	Catch share	10	0.001
Surf clam	Catch share	10	0.022
GOM King mackerel	Non-catch share	20	0.074
SA King mackerel	Non-catch share	19	0.023
Red snapper	Non-catch share	13	0.059
Black sea bass	Non-catch share	11	0.067
Summer flounder	Non-catch share	13	0.183

3.2. Inference method

Fishery management does not always follow a step-wise approach (i.e., modifying output controls such as bag limits or season length a little bit each year); rather, some fisheries may modify their management system substantially from one year to the next. Some examples of substantial changes to the management system include moving from a traditional quota system to a catch share, substantially reducing effort in the fishery to prevent overfishing, or changing the frequency of monitoring from monthly to daily. When management systems are changed substantially, the preferred method of relying on past performance (e.g., the learning curve method) as a predictor of management uncertainty is less reliable.

As an interim approach until performance of the new management system can be measured, managers could infer from other fisheries the expected outcomes of the new management system on management uncertainty. A starting point for these inferences

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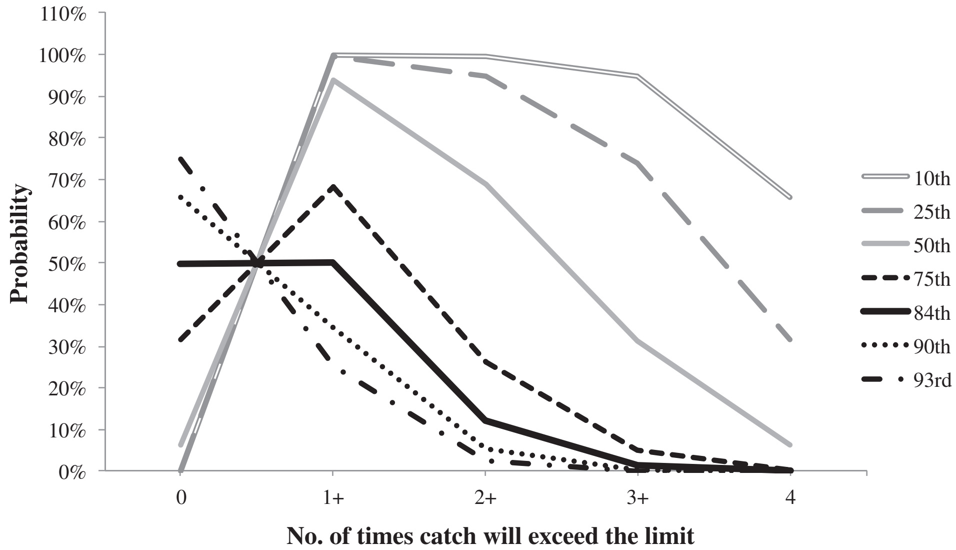

Fig. 6. The probability that the catch limit (e.g., annual catch limit) will be exceeded over a 4-year period, given where the catch limit is aligned with percentile of the ATR probability distribution curve (PDF). The proportion of times the catch limit is expected to exceeded is categorized in 0 times (0), one or more times (1+), two or more times (2+), three or more time (3+), and all 4 times (4).

could be based on the mean or median variance observed in the 17 fisheries we evaluated (see Table 2). However, through time as management uncertainty is calculated for more fisheries, it is anticipated that regional information will be more plentiful and applicable to regional fisheries. The use of inference would likely lead to better management over the transition period to a new management system, as opposed to not setting catch targets, setting arbitrary catch targets, or setting catch targets based on past performance that no longer applies to the fishery.

3.3. Setting catch targets that account for management uncertainty

Once the overall variances of management uncertainty are calculated, either through learning curve, inference or other methods, managers are then able to determine the appropriate risk buffer for setting the target relative to the limit. How targets are set will vary depending on the resource agency managing the fishery, because each agency has their own set of policies and risk procedures. In the United States, NOAA Fisheries (the federal agency responsible for managing marine fisheries) recently published guidance on setting targets and limits under their National Standard 1 Guidelines (74 FR 3178, January 16, 2009). Within those guidelines, NOAA Fisheries recommends setting “annual catch targets” so that the actual catch does not exceed the “annual catch limits” more than once over a 4-year period (1 in 4 standard).[1]

As written, some may interpret this standard to mean that the target level of catch (ACT) should be adjusted relative to the ACL so that in any given year there is 25% chance that catch will exceed the ACL. For example, if a PDF was created based on observed ATRs, you could align the ACL with the 75th percentile of that distribution, so that 25% of the observed ATRs exceeded the ACL in any given year, and the ACT would be set at the median (50th percentile) of your observed ATRs. Such an approach would result in a 25% chance of exceeding the ACL in any given year. However, if the time frame was extended to the next 4 years, the probability that the ACL would be exceeded at least one time is 68.4%. This is because the probability of exceeding the limit in any one year and the probability of overfishing over some number of years is different, with the latter being more likely. To carry on with the example, the probability of exceeding the ACL two or more times is 26.2%, three or more times is 5.1%, and all four times is 0.4%.

Depending on the risk policies of regional fishery management councils,[2] setting the target so that there is a 25% chance that catch will exceed the ACL in any given year may be appropriate, because over a 4-year period the probability of exceeding the limit two or more times is only 26.2%. However, NOAA Fisheries notes that its performance standard of 1 in 4 years was meant to be a signal that regional managers need to reevaluate their management strategy and adapt accordingly so that catch limits are not exceeded so regularly. If the root cause of the overages cannot be addressed, then the target level of catch needs to be adjusted to account for this uncertainty. In any case, it may be appropriate to set a more conservative catch target (i.e., <25% chance in any given year).

We provide two possible percentiles that may be useful for setting catch targets: 84th and 93rd percentiles. Using the same PDF method as before, aligning the ACL with the 84th percentile of the observed ATRs, so that there is a 16% chance of exceeding the ACL in any given year reduces the chances of exceeding the ACL one or more times over a 4-year period to only 50%, compared to 68.4% (Fig. 6). Similarly, aligning the ACL with the 93rd percentile of the observed ATRs would result in a 25% chance of exceeding the ACL one or more times over a 4-year period (Fig. 6).

Unfortunately, determining where the 25%, 16%, or other percent chance of exceeding the ACL in any one year is for a fishery would ideally be based on a PDF that has a long time-series of data

[1] It is important to clarify here that annual catch limits (ACL) should not be confused with the overfishing limit ($F_{OFL} = F_{MSY} * B_{CURRENT}$). The hierarchy under the National Standard 1 Guidelines for limits and targets are: OFL > ABC ≥ ACL ≥ ACT, where the buffer between overfishing limit (OFL) and acceptable biological catch (ABC) accounts for scientific uncertainty and the buffer between ACL and annual catch target (ACT) accounts for management uncertainty. The ABC and ACL are often set equal to one another.

[2] In the United States, regional fishery management councils develop fishery management plans to manage marine fisheries. These fishery management plans are reviewed and approved by NOAA Fisheries, to ensure they meet Congressional mandates.

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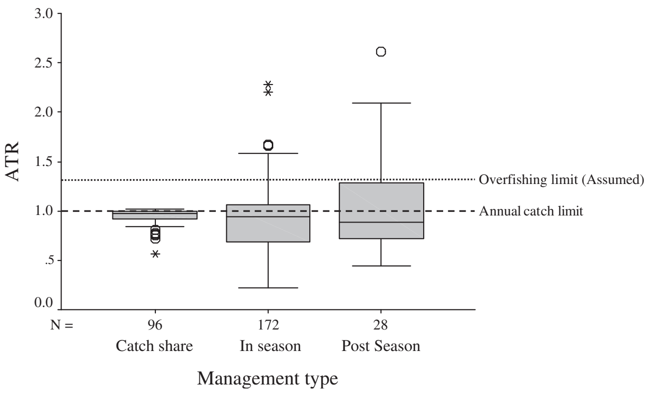

Fig. 7. Observed overages of the targeted catch (>1.0) and assumed overfishing limit (>1.33), if the target was set at 75% of the overfishing limit. Fisheries exceed the targeted catch 2% of time under catch share management, 38% of the time under in-season management, and 38% of the time under post-season management. Fisheries exceeded the assumed overfishing limit 0% under catch share management, 8% of the time under in-season management, and 18% of the time under post-season management.

collected from a fishery. Alternatively, the PDF could be based on the statistics we report here (Table 2). Shertzer et al. (2008) lay out the method for using a probability-based approach to setting catch levels (PASCL), and in Shertzer et al. (2010) they describe how a sequential PASCL can calculate an ACT based on the management uncertainty and the acceptable risk of overfishing. Other software, such as R©, could be used to generate PDFs and density probabilities.

4. Major findings and conclusions

Our analysis of 17 U.S. fisheries shows that a manager's ability to keep a fishery at or under the target catch level can vary substantially among fisheries, and this variance changes depending on the sector of the fishery, the management regime, frequency at which landings are reported, and the magnitude of inter-annual target variability. In general, commercial fisheries consistently had less variance than recreational fisheries, even in comparisons where both sectors were managed in-season. However, we found no significant difference between the median ATRs for these two sectors, each being on average around 0.9 to 0.95, which suggests that these sectors on average hit their catch targets but the number of times it exceeds the target is higher in recreational fisheries due to its higher variance.

We believe the most important lesson of this analysis is that management uncertainty varies among management regimes, and within these regimes reporting frequencies explains a lot of the variation. Similar to Essington (2010), we observed that fisheries managed in-season or post-season exceed their target 37% of the time (ATR > 1.0), while catch share fisheries that report catch daily only exceeded their target 2% of the time (Fig. 7). Furthermore, assuming that an ATR of 1.33 is equivalent to overfishing ($F > F_{MSY}$) because annual catch limits are usually set at 75% of overfishing limit (Restrepo and Powers, 1999; Berkson et al., 2011), then catch share fisheries were theoretically overfishing limit 0% of the time, in-season fisheries were 8% of the time, and post-season fisheries were doing so 18% of the time. These overages are theoretical, because it assumes that all of the fisheries used the 75% rule to set their target and the overfishing limit for each fishery were perfectly known (i.e., no scientific uncertainty existed in the estimate of F_{MSY} and current biomass).

This level of overages at either the target level (37%) or the limit level (8%–18%) indicates that management uncertainty can be a problem, because this uncertainty can often lead to overages of the annual catch limit, and possibly lead to overfishing. Within the U.S., unless manager's account for this management uncertainty, accountability measures will be triggered regularly to either pay back overages or prevent overfishing. Such practices do not maintain maximum sustainable yields within the fishery, and add to the inter-annual variability of the target, which decreases the ability to stay below the ATR (see Fig. 5); creating a negative feedback loop. Although we understand the hesitation to account for management uncertainty—because it can translate into lower target catch—increasing a buffer at the beginning could help prevent the possibility of a negative feedback loop, and in the long run create more stability in the fishery, see (Rosenberg et al., 1993).

We were also surprised to find that only two of our 17 fisheries displayed learning curves. This might be because, until the 2006 reauthorization of the Magnuson–Stevens Fishery Conservation and Management Act, many of the fisheries we examined did not require accountability measures if their actual catch exceeded their targeted level of catch. In the past, stocks were assessed less frequently and accountability measures typically were triggered only when stock assessments identified that overfishing was occurring.

We note that learning curves are only useful when management systems remain similar across years. U.S. policies implemented in recent years have greatly modified the way fisheries are managed. The first mandate occurred in 1996 with the Sustainable Fisheries Act, which required that biological reference points (e.g., F_{MSY}, B_{MSY}, Minimum Stock Status Threshold) be specified for stocks. This new requirement initiated the expansion of stock assessments to define biological reference points, and at the same time identified several fisheries that were overfished or undergoing overfishing. The second revision, already mentioned, occurred in 2006 when the reauthorized Magnuson-Stevens Act required annual catch limits and accountability measures for all managed stocks. This new mandate essentially required managers to develop and monitor annual catch limits and targets for their fisheries. Given the requirements of these two mandates, several fisheries have been modifying their regulations drastically over the past 15 years. Therefore, managers could rely on inference methods to account for management uncertainty, when learning curves are not observed or timeframes of similar management system are insufficient to calculate variances of management uncertainty.

Lastly, it is important to note, that our findings are limited to the fisheries and factors we investigated, and considerably more factors could be examined to better understand overall management uncertainty. Other possible factors include human behavior responses to such things as economic drivers, new fishing regulations, late season fishing effort, etc.; accounting for illegal landings, bycatch; transcription error in reporting landings; the accuracy of landing surveys (if they are modeled based on intercept surveys or based on percentage of wholesalers sampled); law enforcement and observer coverage; and inaccurate projections of available biomass due to scientific uncertainty. With scientific and management uncertainty better accounted for, we would expect fisheries management to be more effective at preventing overfishing and maintaining maximum sustainable yields.

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